A critical review of vector boson + jets Monte Carlos?

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Why study vector boson + jets?

- Precision electroweak, W mass measurement
  We need to know the p_T distribution of the W-bosons, especially at low p_T. Resummation methods can help, but non-perturbative information is also needed.
- Background estimation, we need to know W+n jets, $W + c$+n jets, $W + b$+n jets, $W + b\bar{b}$+n jets, . . .
  These are backgrounds for top, $t\bar{t}$
  Single top s-channel, ($t\bar{b}$), t-channel, tq
  Low mass Higgs, $WH(\to b\bar{b})$
  Any ‘beyond the standard model’ process with missing energy, leptons . . .

Can tree graphs help?

- W, Z + n jets known at tree graph level.
  Madgraph II can generate processes with $\leq$ 9 external particles (madgraph.hep.uiuc.edu)
  Vecbos, W-boson plus up to 4 jets or a Z-boson plus up to 3 jets (theory.fnal.gov/people/giele/vecbos.html)
  Alpgen, W,Z + up to 6 jets
- Problems with tree graphs
  a) Overall normalization is uncertain,
  For example, W+4 jets is O(α_S^4), If scale uncertainty changes α_S by 10%, this leads to 40% uncertainty in cross section.
  b) If we wish talk about hadrons, we must apply fragmentation.
  To use universal fragmentation, we must evolve to a fixed scale.
  Tree graphs require a procedure to combine with parton showers.
  c) Sometimes a new parton process appears at NLO, leading to large change in shapes.

Alpgen, mlm.home.cern.ch/mlm/alpgen/

- W Q Qbar + up to 4 jets
- Z/gamma* Q Qbar + up to 4 jets
- W + up to 6 jets
- W + charm + up to 5 jets
- Z + up to 6 jets
- nW+mZ+kH + up to 3 jets
- Q Qbar plus up to 6 jets
- Q Qbar Q’ Qbar’ plus up to 4 jets
- Q Qbar Higgs plus up to 4 jets
- Inclusive N jets, with N up to 6
- N photons + M jets, with N larger than 0, N+M up to 8 and M up to 6

Can shower Monte Carlos help?

Herwig, Pythia, Sherpa
Advantages

- Good modeling of multiple soft radiation.
  Coherent angular ordered parton shower correct to NLL accuracy, it correctly resums all terms of the form $\alpha_S^n(L^{2n} + L^{2n-1})$ where n is a large logarithm, $L = \ln(s/Q_0^2)$
- Hadronization model included.
- Predictions for all jet multiplicities, hadronization model included.
- Unweighted events, can be fed through detector simulation.
- You are all tooled up to use them . . .

Disadvantages

- Normalization uncertain
- Poor description of region of wide angle emission.

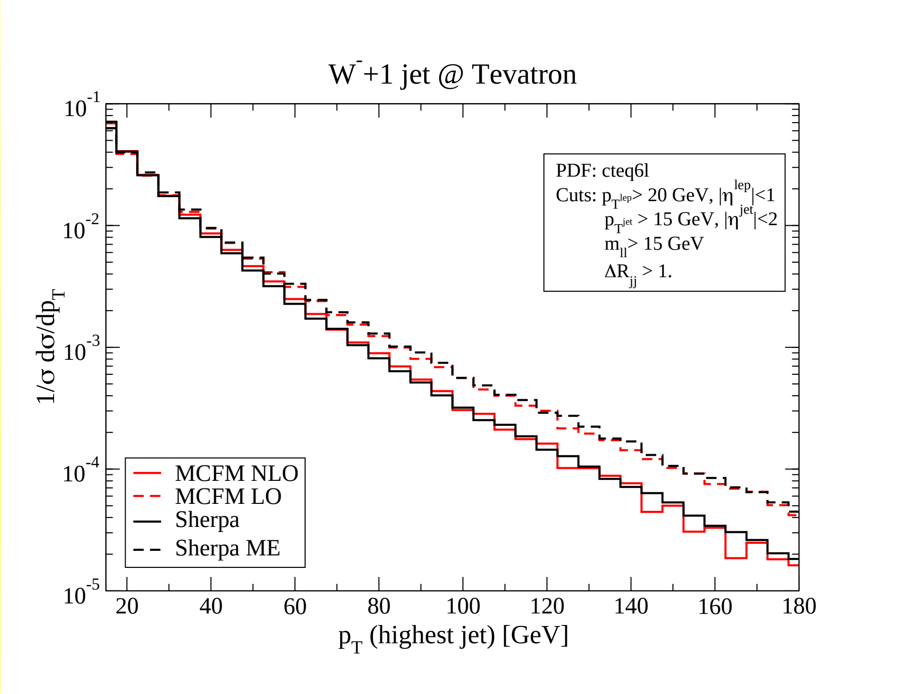
Can one improve on Shower Monte Carlos?

F. Krauss et al, hep-ph/0407365 CKKW, hep-ph/0109231

- Shower Monte Carlo proceeds via Sudakov from factor $\Delta(Q^2, q^2)$, probability of parton transiting from scale Q^2 to q^2 without a branching.
- Divide phase space into two regions, Region I for jet production modeled by the appropriate matrix element, Region II for jet evolution modeled by the parton shower.
- Region I, generate with exact matrix element and include sudakov form factors to enforce subsequent no branching probabilities.
- Region II, veto hard emission in the parton shower in region II.
- Dependence on separation paramter cancels at NLL.

Since fixed order ME's are known, this should be quick to implement.

Results for exclusive W+1 jet rate



- p_T spectrum of jet in exclusive W+1 jet, using Matrix element improved showering scheme.
- Agreement between exact NLO calculation and ME improved shower.

What about NLO event integrators? (MCFM)

Advantages:

- Best information about normalization, until NNLO comes along . . .
- At least some structure for jets
- MCFM based on a subtraction method, matching with Monte Carlo understood, in principle.

Disadvantages:

- Final state composed of jets of quark and gluons, not pions,protons...
- Weighted events
- Relies on availability of virtual corrections for each process.

Can one improve on NLO?

Frixione et al,hep-ph/0305252,hep-ph/0204244

- www.hep.phy.cam.ac.uk/theory/webber/MCatNLO/
- Relies on the appropriate NLO process having been calculated.
- Output is a set of events, which are fully inclusive
- Total rates are accurate to NLO
- NLO results for all observables are recovered upon expansion in α_S
- Currently a limited number of available processes, Higgs boson,
  single vector boson, W/Z,
  vector boson pair, WW,
  heavy quark pair, $Q\bar{Q}$
  lepton pair production, e^+e^-

MC@NLO schematic

$$\langle O \rangle_{\text{sub}} = \int_0^1 dx \left[O(x) \frac{aR(x)}{x} + O(0) \left(B + aV - \frac{aB}{x} \right) \right].$$

Sudakov form factor is the no branching probability,

$$\Delta(x_1, x_2) = \exp\left[-a \int_{x_1}^{x_2} dz \frac{Q(z)}{z} \right],$$

where $Q(z)$ has the following properties:

$$0 \leq Q(z) \leq 1, \quad \lim_{z \to 0} Q(z) = 1, \quad \lim_{z \to 1} Q(z) = 0.$$

MC@NLO schematic

Modified subtraction method

$$\left(\frac{d\sigma}{dO}\right)_{\mathrm{msub}} = \int_0^1 dx\left[I_{\mathrm{MC}}(O, x_{\mathrm{M}}(x))\frac{a[R(x)-BQ(x)]}{x} + I_{\mathrm{MC}}(O,1)\left(B + aV + \frac{aB[Q(x)-1]}{x}\right)\right].$$

MCFM overview

John Campbell and R.K. Ellis

- Parton level cross-sections predicted to NLO in α_S

$p\bar{p} \to W^{\pm}/Z$	$p\bar{p} \to W^{+} + W^{-}$
$p\bar{p} \to W^{\pm} + Z$	$p\bar{p} \to Z + Z$
$p\bar{p} \to W^{\pm} + \gamma$	$p\bar{p} \to W^{\pm}/Z + H$
$p\bar{p} \to W^{\pm} + g^{\star}\,(\to b\bar{b})$	$p\bar{p} \to Zb\bar{b}$
$p\bar{p} \to W^{\pm}/Z +$ 1 jet	$p\bar{p} \to W^{\pm}/Z +$ 2 jets
$p\bar{p}(gg) \to H$	$p\bar{p}(gg) \to H +$ 1 jet
$p\bar{p}(VV) \to H +$ 2 jets	

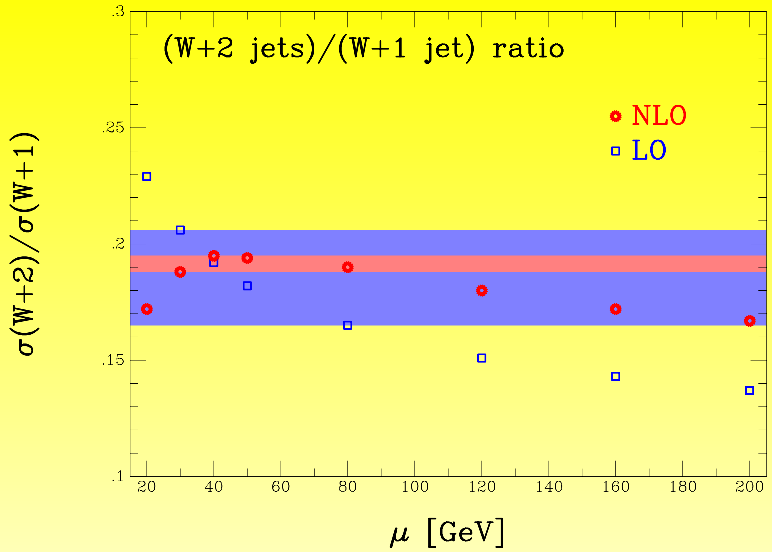
- $\ominus$ low particle multiplicity (no showering)
- $\ominus$ no hadronization
- $\ominus$ hard to model detector effects
- $\oplus$ less sensitivity to μ_R, μ_F
- $\oplus$ rates are better normalized
- $\oplus$ fully differential distributions

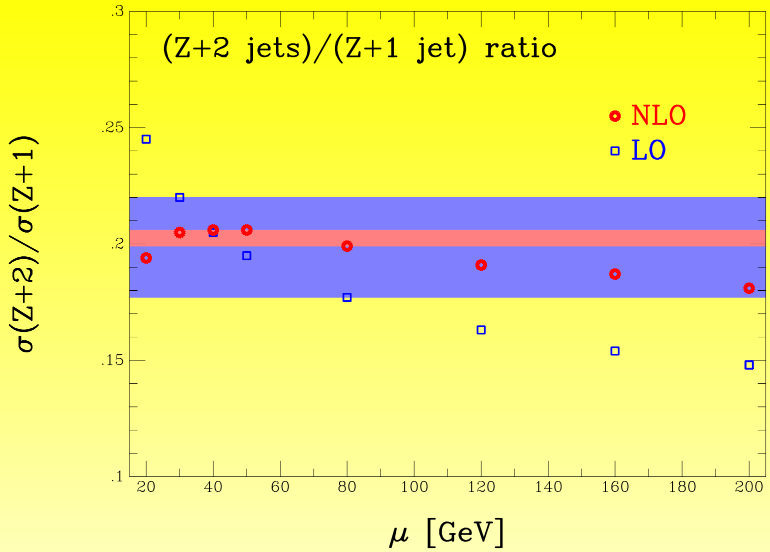
MCFM Information

- Version 3.4.5 available at:
  `http://mcfm.fnal.gov`
- Improvements over previous releases:
  - ⋆ more processes
  - ⋆ better user interface
  - ⋆ support for PDFLIB, Les Houches PDF accord
    ($\longrightarrow$ PDF uncertainties)
  - ⋆ ntuples as well as histograms
  - ⋆ unweighted events
  - ⋆ Pythia/Les Houches generator interface (LO)
  - ⋆ ‘Behind-the-scenes’ efficiency
- Coming attractions:
  - ⋆ more processes ($Z + b$, single top, $\ldots$)
  - ⋆ separate variation of factorization and renormalization scales

$W/Z+$ *jet cross-sections*

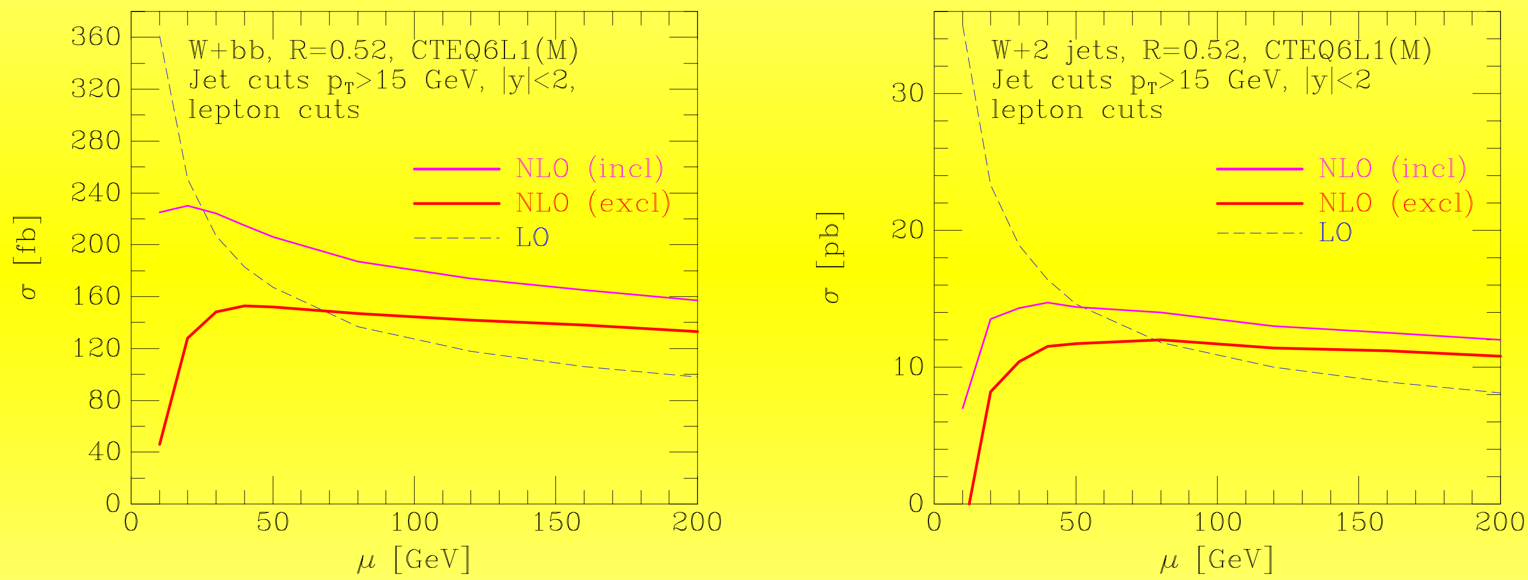
- The $W/Z+2$ jet cross-section has only recently been calculated at NLO and should provide an interesting test of QCD (cf. many Run I studies using the $W/Z+1$ jet calculation in DYRAD)
- For instance, the theoretical prediction for the number of events containing 2 jets divided by the number containing only 1 is greatly improved.





Scale dependence

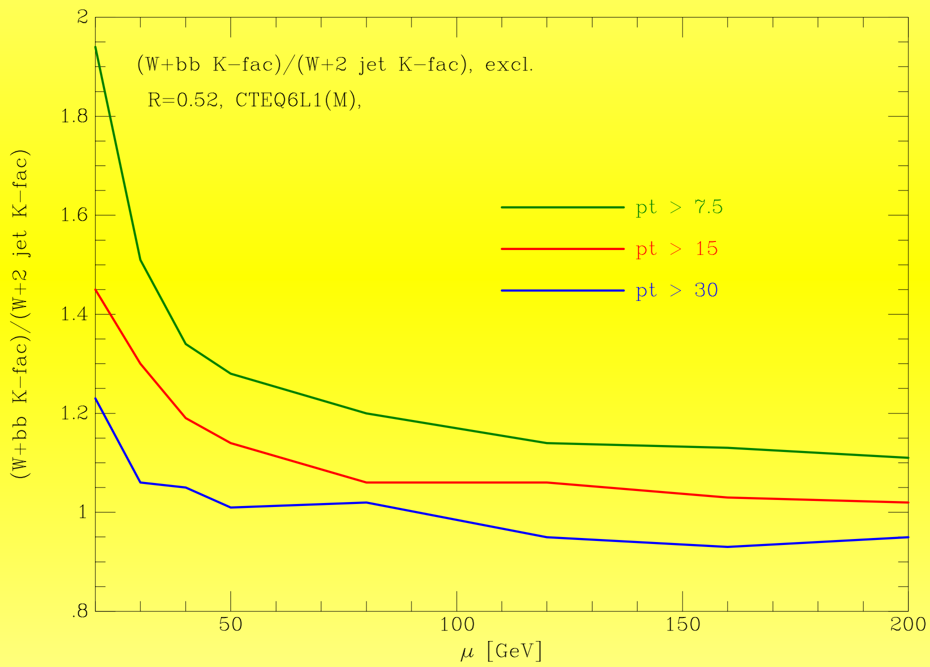
- Usual scale dependence, much reduced at NLO. Corrections are modest at typical scales, $\mu \sim M_W$.



- Exclusive cross-sections stable over a large range of scales.
- Inclusive result (allows $Wb\bar{b}j$, $W+3$ jet configurations) shows more scale dependence, as expected (but still better than LO).

K-factor ratio

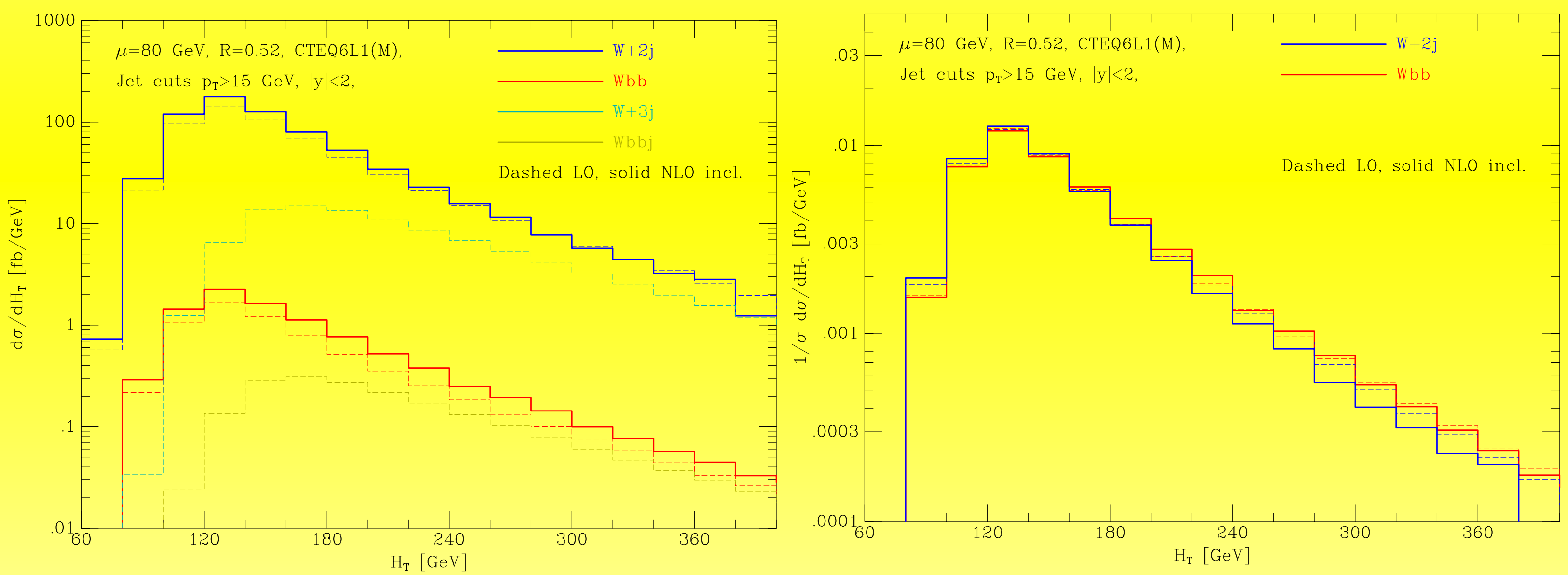
- Important for CDF's "Method 2". Essentially, is a lowest order estimate of ($Wb\bar{b}/W + 2$ jets) reproduced at NLO?



- A qualified "yes" - it is for scale choices around 50 GeV or greater and p_T cuts of about 15 GeV or greater.
- As the jet p_T cut is lowered, the ratio gets worse (increases).

Kinematic distributions

- NLO behaviour may provide clues to processes with more jets ($\to$ relevant for $t\bar{t}$), especially for more inclusive variables such as $\sum E_T(\text{jet})$ and $H_T = \sum_{\text{event}} E_T$.



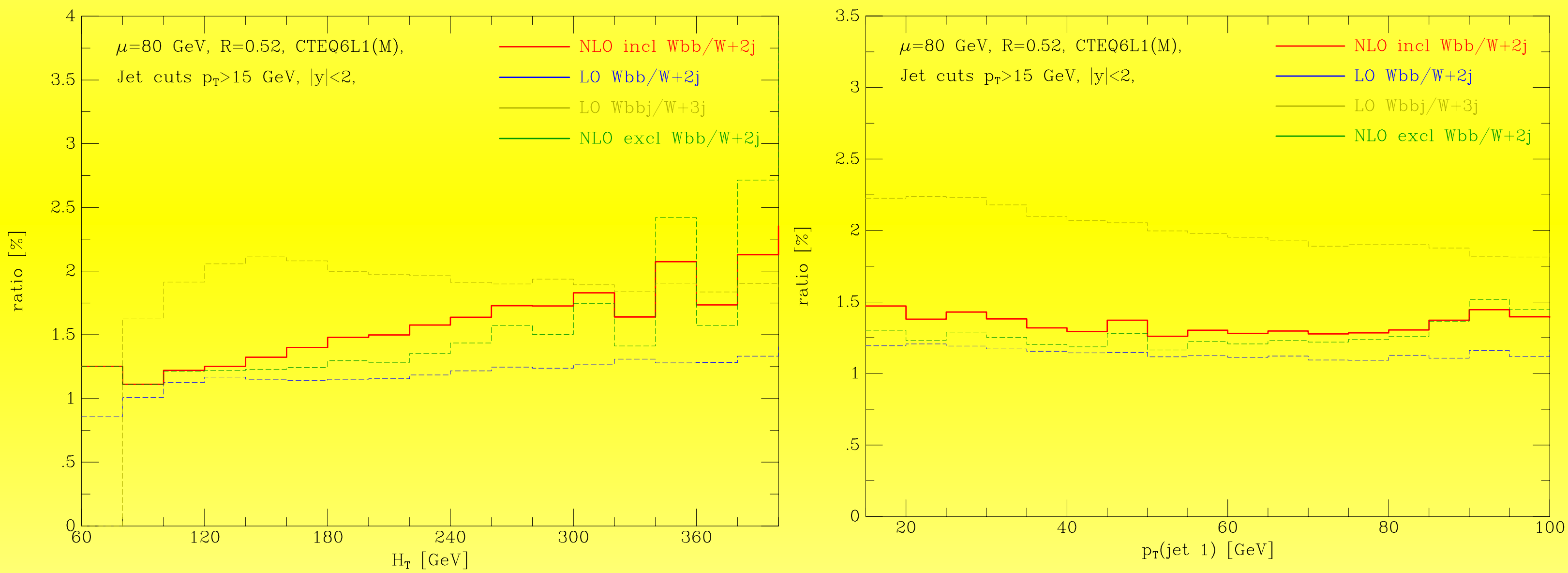
- $Wb\bar{b}$ shape is relatively unchanged at NLO, compared to $W + 2$ jets.

NLO predictions

- At NLO, there is a change of shape in the H_T distribution.

Lowest order
Lowest order+jet

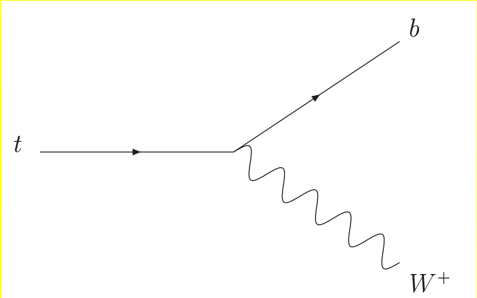
NLO inclusive
NLO exclusive



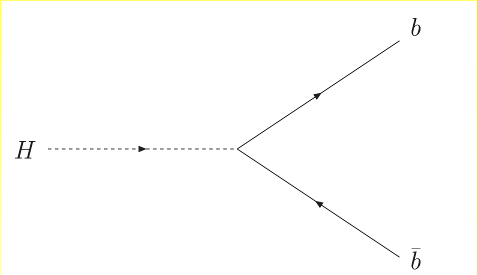
- This change is not entirely due to the extra $W + 3$ jet events allowed in the inclusive sample.
- The p_T distribution of the hardest jet shows no change in shape.

Heavy flavour as a background

- Events containing jets that are heavy-quark tagged are important for understanding both old and new physics:
  - ⋆ Top decays $t \to W + b$



  - ⋆ Much new physics couples preferentially to massive quarks, for instance a light Higgs with $m_H < 140$ GeV decaying to $b\bar{b}$

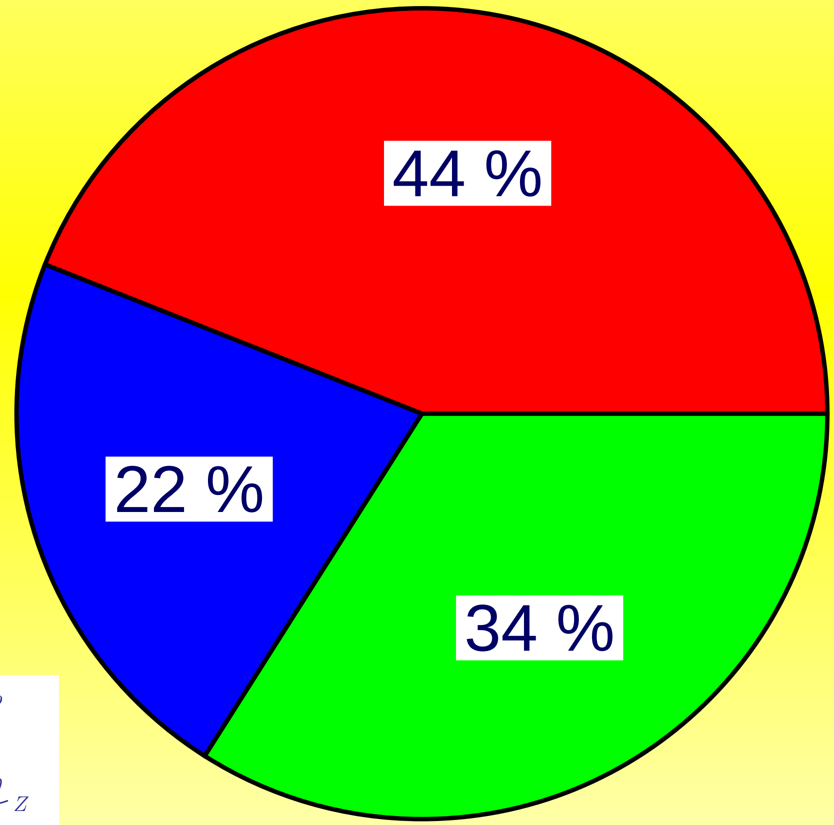


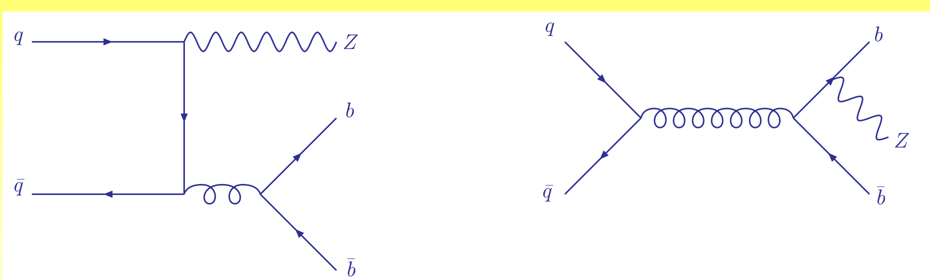
$Z + b$ at NLO - Run II

Campbell et al, hep-ph/0312024

- $p_T^{\rm jet} > 15$ GeV, $|\eta^{\rm jet}| < 2$
- $\sigma(Z + \text{ one } b \text{ tag}) = 20$ pb
- Fakes from $Z+$ jet events are significant
- Prediction for ratio of $Z + b$ to untagged $Z + \text{jet}$ is

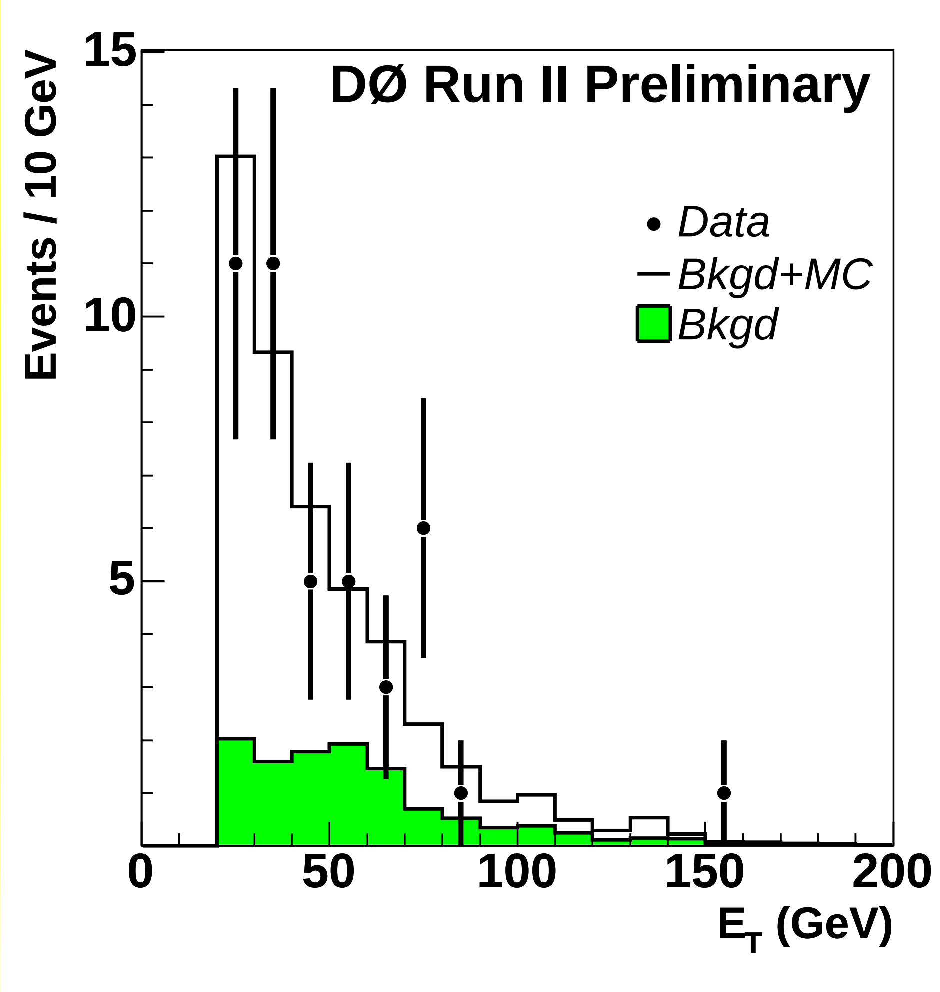
  0.02 ± 0.004





Experimental result

- Based on $189\ \mathrm{pb}^{-1}$ of data from Run II



Preliminary ratio of cross-sections:

$$\frac{\sigma(Z+b)}{\sigma(Z+j)} = 0.024 \pm 0.07$$

compatible with the NLO prediction

$Z + b$ process in the next version of MCFM will allow a much better comparison with the analysis

MCFM Outlook

- The $W+$ jets channel (including heavy quarks) is very important for many studies in Run II.
- Unfortunately, for events with many jets we are limited to LO predictions for rates and distributions. You can have loops, or you can have legs, but you can't yet have both.
- The highest multiplicity that is currently available is production of $Wb\bar{b}$ and $W+2$ jets.
- Implications for Run II analyses.
  - ⋆ Results suggest that some relevant observables do not suffer from large NLO effects and we can proceed with more confidence in analyses based on LO tools.
  - ⋆ However, beware of variables that change shape at NLO (H_T).
  - ⋆ These statements are heavily dependent on scale choices.

Current research directions

- $W + 3{,}4$ jet cross-sections at NLO
  - ⋆ New technology needed: ready for Run II?

Nagy and Soper, hep-ph/0308127
Giele and Glover, hep-ph/0402152

- Inclusion of b mass effects in $Wb\bar{b}$ and $Zb\bar{b}$
  - ⋆ Technology available: some efforts are underway ... c.f. $Hb\bar{b}$

W. Beenakker et al., hep-ph/0211352
S. Dawson et al., hep-ph/0311216

- Merging of existing NLO calculations with a parton shower
  - ⋆ Possible: MC@NLO has yet to be applied to $W/Z+$ jets
- Further study of recent ideas regarding improving parton showers (most promising in the short term)
  - ⋆ Matrix elements corrections - CKKW, Krauss et al ...
- Comparisons of all approaches amongst themselves and with data is important.